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SEARCH FOR LEPTONS PRODUCED IN ASSOCIATION WITH PROMPT MUONS IN HADRONIC INTERACTIONS

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Dileptons observed in hadronic collisions at high energy can serve as a sensitive indicator of the production of new kinds of particle states. Any such states which are pair-produced, and which have semileptonic or leptonic weak decays, will contribute to the dilepton signal. In particular, if a $\Delta C = \Delta Q$ rule holds in charm decay,[1,2] then charmed particles are expected to provide dileptons of opposite electric charge. In addition, the leptons from charm decay processes should appear preferentially at low Feynman-x values and small transverse momenta.[3] Because dimuons can originate either from electromagnetic or weak-decay sources, while $\mu^{\pm}e^{\mp}$ pairs can arise only from weak decays, the relative yield of μe and $\mu\mu$ events provides, in general, a measure of the contribution of weak decays to dilepton production, and, in particular, the contribution from charm production to the dilepton yield.

We have performed an experiment at Fermilab to investigate dilepton production in neutron-beryllium collisions near 300 GeV/c. The event trigger in this study was provided by a muon having both low momentum ($6.5 \leq p \leq 50$ GeV/c) and low transverse momentum ($0.2 \leq p_T \leq 1.2$ GeV/c). Additional leptons, with momenta between 10 and 40 GeV/c and transverse momenta less than 1.2 GeV/c, produced in association with the trigger muon, were detected simultaneously. A general discussion of the two-arm spectrometer and the nature of the muon trigger may be found in the previous letter.[4] We now discuss the specific instrumentation in the forward arm relevant to the identification of the associated leptons.

Electrons were identified in a 38 element lead-lucite shower detector (e), indicated in Fig. 1. Each element was 2 inches wide and 3 feet long, and constructed of 8 interleaved layers of 0.25 inch lead and 0.25 inch lucite. An 0.75 inch lead converter, followed by a 16 element hodoscope (H2), was located upstream of the shower detector to sample the shower early in its development, and thereby improve hadron rejection.

Studies of shower-detector response and energy resolution were performed in the M5 test beam at Fermilab and by using the photon component of the M3 neutral beam. In the latter case, the beryllium target was replaced by a thin lead target, and electron-positron pairs produced by photon conversions in the lead were then used to calibrate the shower-counter array and monitor its stability. The energy resolution (standard deviation) of the shower detector was measured to be 9% for 30 GeV/c electrons.

To establish that a track in the forward arm of the apparatus was an electron candidate, the reconstructed track had to satisfy the following criteria:

1) The energy/momentum (E/p) ratio had to be between 0.75 and 1.25; where E represents the energy deposited in the two shower elements nearest to the particle's trajectory, and p refers to the particle's momentum as determined by the spark-chamber spectrometer.

2) The pulse height in the H2 counter associated with the particle's trajectory had to exceed 2.3 times the

minimum-ionizing peak value.

3) The ratios of energies in the two shower counters nearest the track had to be consistent with that of the radial spread expected from an electron shower.[5]

Approximately 1.5% of all tracks satisfied the above criteria; the remaining tracks were designated as hadrons (h). About 57% of the real electrons survived all of the above cuts.

The observed number of μe events can be expressed as a superposition of contributions from various sources as follows:

$$N(\mu^{\pm}e^{\mp}) = N_1(\mu^{\pm}e^{\mp}) + N_2(\mu^{\pm},\pi^{o} \to \gamma\gamma) + N_3(\mu^{\pm},\pi^{o} \to e^{+}e^{-}\gamma) + P_F \times N_4(\mu^{\pm}h^{\mp}) \qquad (1)$$

where N represents the measured yield of oppositely charged pairs; N_1 is the yield from interesting processes, such as charm decay; N_2 is the μe yield in which the electron results from the decay of a $\pi^{o}(\pi^{o} \to \gamma\gamma)$ with a subsequent external conversion of one of the photons; in N_3 the electron results from the Dalitz decay of a π^{o}. The last term represents the contribution from hadron "feed-throughs", where N_4 is the yield of muon-hadron pairs and P_F is the probability that the hadron satisfies the criteria for electron candidacy described above. An expression similar to that of equation (1) can be written for like-sign μe pairs; here, however, we assume that the prompt electron signal in the like-sign pair data can be ignored[2] and consequently we set $N_1(\mu^{\pm}e^{\pm}) = 0$. The terms involving π^{o} decay are independent of the charge of the trigger muon, and contribute equally to $N(\mu^{\pm}e^{\mp})$ and to $N(\mu^{\pm}e^{\pm})$. The hadron feed-through contribution is more serious, however, because it is correlated with the charge of the trigger muon. (Overall, we find 20% more oppositely-charged than like-charged muon-hadron pairs.)

We can infer the contribution of hadron feed-throughs to the $\mu^{\pm}e^{\mp}$ signal by measuring directly the two π^{o} conversion terms in the $\mu^{\pm}e^{\pm}$ data. This was done by running the experiment with several different thicknesses of lead converter placed downstream of the Be target, to examine the apparent electron/hadron fraction (F) in the μ-triggered data as a function of the number of radiation lengths (λ) of material; the fraction F is defined as follows:

$$F(\lambda) = N(\mu^{\pm}e^{\pm}, \lambda)/N_4(\mu^{\pm}h^{\pm}). \tag{2}$$

The measured data points (see Fig. 2) were fit to a straight line as a function of λ. Extrapolating this fit to $\lambda = -.008$ radiation lengths determines the contribution of all π^{o} sources to the μe signal. The remaining excess in $F(\lambda)$ at this extrapolated point (P_F) is the probability for hadron feed-through in the $\mu^{\pm}e^{\pm}$ data, and therefore also for the $\mu^{\pm}e^{\mp}$ events. (Again, we have assumed that for like-charged μe events there is no true prompt signal.)

Consequently, using the results of Fig. 2, we can write the following expression for the prompt contribution to the $\mu^{\pm}e^{\mp}$ signal:

$$\begin{aligned} N_1(\mu^{\pm}e^{\mp}) &= N(\mu^{\pm}e^{\mp}) - N(\mu^{\pm}e^{\pm}) \\ &\quad -(N_4(\mu^{\pm}h^{\mp}) - N_4(\mu^{\pm}h^{\pm})) \times P_F \end{aligned} \tag{3}$$

Table I displays the values of each of the quantities given in equation (3) for three bands of electron momentum (integrated over all momenta of the trigger muon). The data in Table I provide no indication of a significant excess in the prompt $N_1(\mu^{\pm}e^{\mp})$ events.

Muons in the forward arm of the spectrometer were identified in a 12 element liquid-scintillator hodoscope (μ) located downstream of a 12 ft. long steel filter (see Fig. 1). Reconstructed tracks were labeled as muon candidates if their trajectories extrapolated to muon counters in which a minimum-ionizing pulse height was observed. Two percent of all tracks reconstructed in the forward arm were designated as muons.

The yield of prompt, oppositely-charged dimuons is obtained in a manner analogous to that used in the μe analysis:

$$\begin{aligned} N_1(\mu^{\pm}\mu^{\mp}) = {} & N(\mu^{\pm}\mu^{\mp}) - N(\mu^{\pm}\mu^{\pm}) \\ & - (N_4(\mu^{\pm}h^{\mp}) - N_4(\mu^{\pm}h^{\pm})) \times P_D \end{aligned} \tag{4}$$

where P_D is the probability for pion decay (correcting for the fact that about 90% of all hadrons are pions). The quantities in equation (4) are also displayed in Table I. There is a clear excess of prompt $\mu^{\pm}\mu^{\mp}$ events. The mass distributions for dimuons are shown in Fig. 3a (The mass resolution is about ±15%).

To compare the μe and $\mu\mu$ yields, the two data sets have been normalized to the same geometric acceptance and incident flux; also the μe data have been corrected for additional losses due to the electron cuts. The results are shown, as a function of momentum of the lepton in the forward arm, in Fig. 3b and in Table I.

The absence of prompt $\mu^{\pm}e^{\mp}$ events suggests that the observed excess of $\mu^{\pm}\mu^{\mp}$ events is primarily electromagnetic in origin. Integrating over forward-lepton momenta from 10 to 40 GeV/c, the relative rate for μe to $\mu\mu$ production is 0.14 ± 0.13. This result can also be expressed in terms of production cross sections as follows:

$$\begin{aligned} N_1(\mu^{\pm}e^{\mp}) &= \sigma^{W} B_{\mu} B_{e} A^{W} \\ N_1(\mu^{\pm}\mu^{\mp}) &= \sigma^{em} A^{em} + \sigma^{W} B_{\mu}{}^{2} A^{W} \end{aligned} \tag{5}$$

where σ^{W} is the cross section for producing the parent particles which decay weakly into μe, or $\mu\mu$ pairs; σ^{em} is the cross section for electromagnetic production of dimuon pairs; the B and A factors represent decay branching ratios and acceptances for the appropriate processes. A^{em} for our apparatus was determined using the dimuon production data of Anderson, et al.[6] A^{W} was determined assuming the form $\exp(-5x) \cdot \exp(-1.5p_T{}^2)$ for the invariant cross section for charmed particle production. Charmed-particle decay was assumed to proceed isotropically via the process $C \rightarrow K^*(890)\ell\nu$.[7] Assuming further that $B_e = B_{\mu}$, we obtain:

$$\frac{\sigma^{W} B_{\mu}{}^{2}}{\sigma^{em}} = .23 \pm .21 \tag{6}$$

Finally, the $\mu^{\pm}e^{\mp}$ data can be used to derive an upper limit for the associated production of charmed particles. If we assume that at least a two standard deviation excess of oppositely charged to like-charged pairs, over the full range of electron momenta (10 to 40 GeV/c), would be regarded as significant, then the derived upper limit at 95% confidence, for associated charm production, with subsequent decay into leptons, is: $\sigma_{c\bar{c}} \cdot B(C \rightarrow \mu + x) \cdot B(C \rightarrow e + x) < 340$ nb nucleon. If the branching ratios are 15%, this implies that the upper limit for associated charm production is: $\sigma_{c\bar{c}} < 15$ μb/nucleon. It should be stressed that this upper limit is more stringent than those obtained from $K\pi$ mass searches, because the semileptonic or leptonic decays of both charmed mesons and charmed baryons can, in principle, contribute to the signal.

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REFERENCES

[1] M. K. Gaillard, B. W. Lee, and J. Rosner, Rev. Mod. Phys 47, 277 (1975).

[2] The situation is completely analogous to that of strangeness changing semileptonic decays. It must be noted that the phenomenon of $D^o-\bar{D}^o$ mixing could dilute the opposite-sign lepton correlation. However, this mixing is expected to be much smaller than $K^o-\bar{K}^o$ mixing: G. Feldman, et al. Phys. Rev. Lett. 38 1313 (1977) provide an upper limit of 16% for $D^o-\bar{D}^o$ mixing.

[3] J. Sullivan, in Particle Searches and Discoveries - 1976, (Vanderbilt Conference), R.S. Panvini, ed.

[4] D. Spelbring et al., Phys. Rev. Lett. (1977), preceding paper.

[5] This cut uses the radial spread of the electron shower, as measured in the M5 test beam, to calculate the energy distribution expected in the shower elements. The measured ratio of energies of neighboring counters is required to be within 20% of that predicted from test-beam data.

[6] K. J. Anderson et al. Phys. Rev. Lett. 37, 799 (1976).

[7] The actual acceptance for the leptons (ℓ) was calculated using the specific decay $D^o \rightarrow K^*(890)\ell\nu$, and is assumed to be representative of semileptonic decays of all charmed particles. The acceptance for leptons in the forward arm is insensitive to the hadronic mass in the decay; however, this is not the case for the muon arm (see Footnote 9 of reference 4). For a muon trigger, the average acceptance for an accompanying muon in the forward arm from electromagnetic sources is ~ 8% while the acceptance for an accompanying electron from D^o decay is ~ 9%.

TABLE I

CALCULATION OF EXCESS OF OPPOSITELY CHARGED DILEPTONS

μe Events [a]

Electron Momentum (GeV/c)	$N(\mu^{\pm}e^{\mp})$	$N_4(\mu^{\pm}h^{\mp}) - N_4(\mu^{\pm}h^{\pm})$	P_F	$N(\mu^{\pm}e^{\pm})$	$N_1(\mu^{\pm}e^{\mp})$ [b]	$N_1(\mu^{\pm}e^{\mp})$ normalized to $\mu\mu$ data
10 - 20	597	7228	.008	538	5 ± 33	7 ± 28
20 - 30	342	3660	.007	266	51 ± 24	33 ± 22
30 - 40	148	1623	.007	142	-5 ± 16	1 ± 14
					51 ± 47	41 ± 37

$\mu\mu$ Events [a]

Forward Muon Momentum	$N(\mu^{\pm}\mu^{\mp})$	$N_4(\mu^{\pm}h^{\mp}) - N_4(\mu^{\pm}h^{\pm})$	P_D	$N(\mu^{\pm}\mu^{\pm})$	$N_1(\mu^{\pm}\mu^{\mp})$ [b]
10 - 20	527	3770	.018	287	162 ± 28
20 - 30	292	1438	.011	194	92 ± 22
30 - 40	127	522	.008	92	31 ± 15
					285 ± 38

(a) See text for definition of symbols.

(b) This is the measured prompt signal, see text for further explanation.

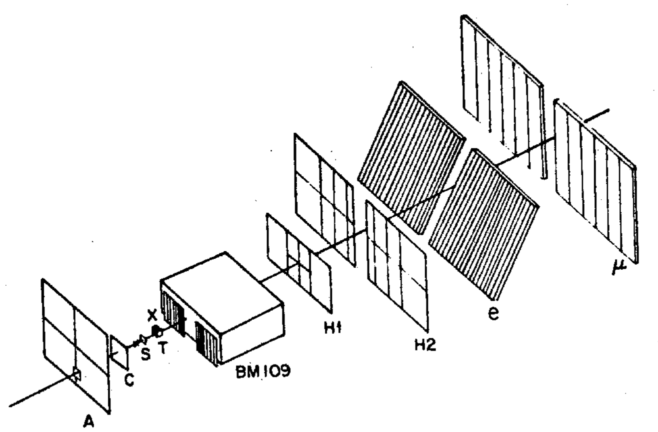

Fig. 1: Schematic of hodoscopes and counters in the forward arm of the spectrometer.

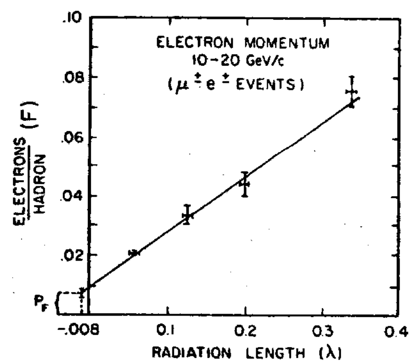

Fig. 2: Ratio of electrons to hadrons observed in the forward arm of the spectrometer for ($\mu^{\pm}e^{\pm}$) events plotted as a function of radiation lengths of material downstream of the interaction point. The point at λ = .06 is the normal running condition. The three points at larger values of λ have increasing amounts of lead converter added downstream of the Be target. P_F is the value of the feed-through probability for hadrons in the 10-20 GeV/c momentum band.

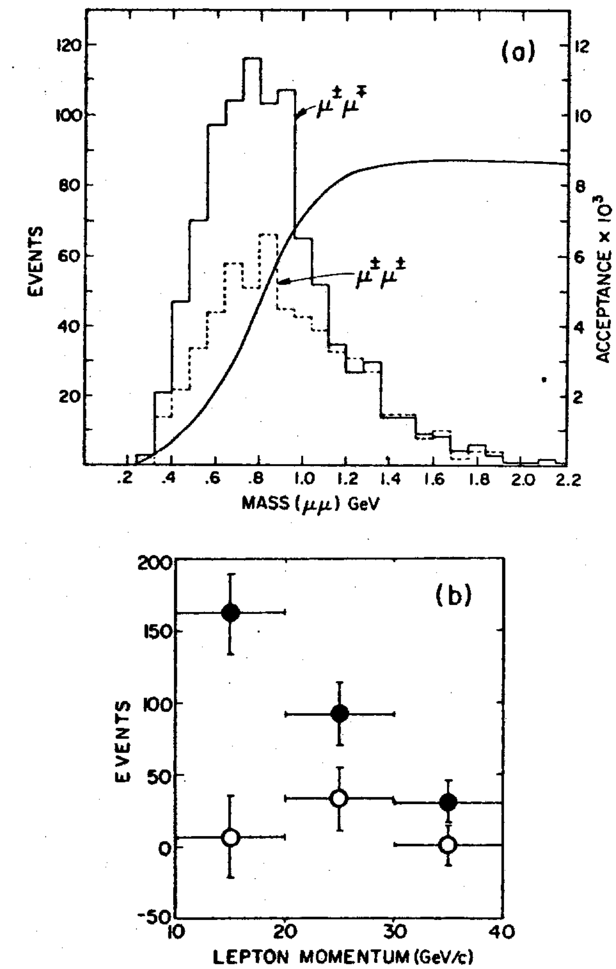

Fig. 3: (a) Dimuon mass distributions observed combining the trigger muon with a muon in the forward arm of the spectrometer. The acceptance, which has not been folded into the data, is also shown in the figure.

(b) Corrected number of leptons in the forward arm as a function of lepton momentum (integrated over all muon triggers). The closed circles refer to muons detected in the forward arm, open circles to electrons.